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METHODS AND APPARATUS FOR THE STUDY OF EVAPORATION.

By C. F. MARVIN, Professor of Meteorology. Dated June 21, 1909.

[Continued from the *Monthly Weather Review*, April, 1909.]

II.—INSTRUMENTS.

The instruments described in the following pages were devised to meet the needs of the campaign of work upon the evaporation of water from lakes and reservoirs, which has recently been undertaken by the Weather Bureau.

Although some of the devices were made up fully two years ago, yet they have only recently been employed in actual observations, and the object of the present paper is to bring the new instruments to the attention of those who may wish to use apparatus of this character.

We mentioned in the first section¹⁰ of this paper that our present studies are confined essentially to the phenomena of evaporation from free water surfaces, and the apparatus, therefore, is designed more especially for the measurement of evaporation of water from pans.

GENERAL METHODS OF MEASUREMENT.

No method is known by which we can directly measure the water evaporated from an extended surface of water, soil, ice, snow, etc., as they ordinarily occur in nature. All we can do is to isolate, for example, a pan of this water, soil, snow, or ice and ascertain how much it loses by evaporation from day to day or hour to hour. Two general methods are available, viz:

- (1) The weighing method.
- (2) The volumetric method.

All existing apparatus for measuring evaporation, with scarcely an exception, belong in one or the other of these classes. If a psychrometer, for example, is regarded as an evaporimeter then we need to make a separate class.

The Weighing Method.

The weighing method when available is probably the most exact of any, and perhaps it alone can be employed in the measurement of evaporation from ice, snow, damp soils, growing vegetation, etc. This method, nevertheless, is subject to sharp limitations that often make it wholly unavailable. In many cases it is of great importance that the isolated mass of material be relatively very great as compared with the loss by evaporation in the interval between observations. To weigh the loss under such conditions will generally require costly balances operating under conditions that entail special difficulties, or may be wholly incompatible with the general possibilities of the situation. The weighing method is, therefore, generally unavailable in all extensive field observations.

The Volumetric Method.

The volumetric method resolves itself nearly always simply into the measurement of the depth of water remaining in the evaporating pan or other container. Important errors affect this method and must be carefully accounted for. Among these may be mentioned:

- (a) The formation of waves and ripples on the water, rendering it difficult to define and measure the mean level of the surface.
- (b) The wind may drive the water from the lee to the windward side of the pan, causing false readings of changes in level.
- (c) If not very solidly supported small tiltings and mechanical alterations in the position of a pan may be caused every

time an observer approaches it to make a reading. Serious errors may be made in the measurements by such causes.

(d) Pans of considerable size floating in the water, and other pans to a lesser degree, may sometimes undergo such mechanical deformations or volumetric alterations as to produce changes in the level of the water-surface that do not correspond to real evaporation.

All possible causes of error such as those we have mentioned must of course be very carefully eliminated. Even in those regions where evaporation is very active it must nevertheless be measured in units of hundredths or even thousandths of inches, and trained scientists are well aware that measurements of this order of exactness cannot be carried forward from day to day except by the aid of apparatus whose essential parts retain the most definite and invariable relations.

Evaporation pans.—Probably the most suitable apparatus for the study of evaporation from an extended water surface consists of a large pan of water provided with means by which the loss of water can be measured or automatically recorded. Experience has shown that the size of the pan and the distance of the water below the rim will make very little difference within reasonable limits of variation. This does not mean that the actual evaporation in a 2-foot pan, 6 inches deep, will be the same as from a 10-foot pan, 6 feet deep, for example. The temperature of the water in the two pans would doubtless prove to be very different; but when this and other differences have been fully taken into account the evaporation will generally be found to be quite the same.

The sheltering effect of the rim of the pan is always important and to minimize this pans of large diameter—4 feet or more—should be used as far as possible. In general the water surface may be kept within 2 inches, or even less, of the rim of the pan. A greater depth may be necessary if water is likely to be splashed out by strong winds. So, likewise, in regions subject to heavy rainfall the height of the rim must be great enough to prevent the overflow of the pan by heavy rains. Circular pans about 4 feet in diameter and 10 inches deep, made of galvanized sheet iron, constitute a good working size.

Rain-sheltered pans.—When rainfall occurs frequently and in considerable amounts it is practically impossible to accurately determine the evaporation if the rain is permitted to fall into the evaporation pan. In the writer's opinion the only plan to follow is to roof over the evaporation pan so that no rain can fall into the apparatus. This roof must not obstruct the perfectly free action of the wind underneath. A pan so exposed will of course show a different march of temperature conditions, but the evaporation equation which will ultimately be developed will take account of this and there are many great advantages in the use of rain-sheltered pans. This plan has been recently put in operation by F. De Willson on the Panama Canal Zone. Evaporation often goes on continuously during showers, as the air is not then necessarily saturated.

Installation of pans.—To avoid and minimize the errors due to change of position and deformation, mentioned above under (c) and (d), the customary galvanized sheet iron pans must be bedded as perfectly and evenly as possible on rigid supports, and when floated in the water the pans must be trussed and ribbed, or otherwise reenforced, so that deformations do not result from the gentle wave motions of the water.

The still-well.—We now come to the details of the actual measurement of the water that passes out of one of our evaporation pans. These measurements aim to locate accurately the level of the water surface at each observation, so that the lowering of the surface represents the loss of water by evaporation. Any exposed water surface is almost always disturbed by large or small wavelets so that some artifice must be resorted to that will suppress the wave motion and realize the equivalent level the water would assume if stationary. We

¹⁰ *Monthly Weather Review*, April, 1909, 37:141.

shall apply the term still-well to any expedient that accomplishes this result.

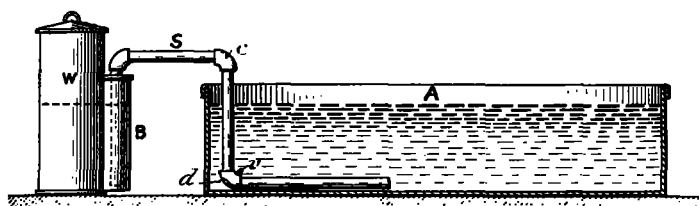


FIG. 2.—Still-well and siphon (Marvin).

The writer has devised a form of still-well, shown diagrammatically in fig. 2, that can be varied to meet almost any set of conditions that generally arise. In the figure *A* is the evaporation pan, *W* is the still-well consisting of a separate vessel adapted to the particular purpose required. At *B* a small bay-window-like extension is securely soldered on the surface of *W* and the two chambers communicate with each other by means of a suitable hole in the wall of *W* near the bottom of *B*. The pan and still-well are put into hydrostatic communication by means of the siphon *S* which is made of the ordinary so-called $\frac{1}{2}$ -inch galvanized-iron water pipe. It was a long time before a satisfactory plan was hit upon for easily filling the siphon perfectly. The solution however was found in the vent-tube *v*, which is shown enlarged in fig. 3. A small pliable copper tube, *cc*, is run through a hole drilled in the angle of the elbow *d* and terminates as high up in the elbow *c* as practicable. It is not essential that the tube fit water tight in the elbow *d*. Thus constructed the siphon can be easily adapted to almost any situation, leaky joints are easily avoided and the absence of rigid connections between the pan and the still-well removes a possible source of error caused by small changes in the relations of the two parts due to variable mechanical strains, temperature changes and the like.

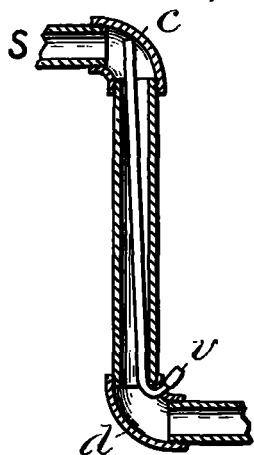


FIG. 3.—Detail of siphon (Marvin).

To fill the siphon a short piece of rubber tubing is slipped over the vent at *v* and the air deliberately sucked out of the siphon. *W*, of fig. 2, must of course contain sufficient water to seal the siphon in *B*. The operator will notice a distinct check in the outflow of the air when water enters the fine copper tube. This constitutes a definite signal that the siphon is full and the rubber tube may then be removed. It is better to incline the siphon a little so that the elbow *c*, while filling, is the highest point in the system.

The flow of water through a siphon of even $\frac{1}{2}$ -inch pipe is relatively slow, and consequently very considerable wave agitation in the pan produces no appreciable alteration of the free water surface in the still-well. It is generally best to carry the end of the siphon in the pan out to its center to minimize the errors due to tilting of the pan and to banking up of the water on one side by the wind.

Where the conditions are such that a still-well of relatively small dimensions suffice, it will be much better to make this an integral part of the pan itself. This plan should also be followed especially in the case of floating and suspended pans even when the still-well is of considerable relative size.

Errors incident to the use of still-wells, floats, etc.—Whenever a float is used on an evaporation pan, or a still-well employed, a certain source of error is introduced that is very easily corrected for, but the error is nevertheless often quite ignored. This is readily understood from fig. 4.

Suppose we are using a large float *F* riding directly upon the water surface of a pan. Obviously the surface from which evaporation takes place is not the whole area of the pan, but is this area less the sectional area of the float at the water line. On the other hand the movements of the float show only the changes of level of the whole water contents of the pan. If the area of the float is one-half the area of the pan then a given change in level of the float will indicate only one-half the actual evaporation, that is, such as would be shown by this same pan if without the float. The same thing results when a still-well is employed. Either designedly or incidentally there will be little or no evaporation possible from the water surface in the still-well, consequently all the evaporation takes place only in the pan while the change in level affects both the pan and the still-well, so that the indicated is always less than the actual evaporation depending on the relative sectional areas.

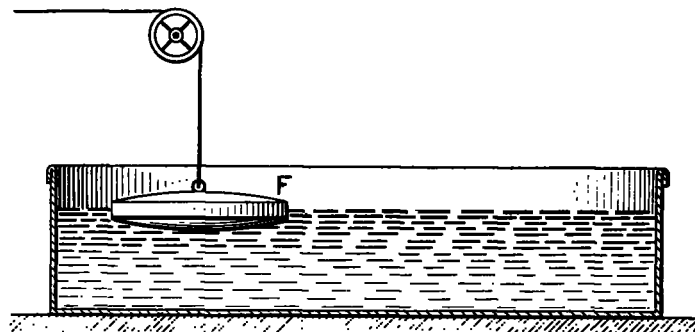


FIG. 4.—Illustrating still-well and float errors.

Let A = area of free surface of water that evaporates, and a = area of float or still-well. This area must include all free water surfaces not subject to appreciable evaporation and that are in hydrostatic communication with the evaporation pan. We shall then have: True evaporation = Observed change of level $\times \frac{A+a}{A}$. Suppose that the area of the still-

well or float is 3 per cent of the area of the free evaporating surface. The foregoing expression means simply that all direct readings of the evaporation are 3 per cent too small and should be corrected accordingly. We shall point out later (p. 186) how the float and still-well error can be automatically compensated for in the measuring instruments themselves and thus avoid the tedious correction of observations and records otherwise necessary.

Having in one way or another established an undisturbed water surface, change of level may be measured by the aid of numerous devices that have been proposed or used. These will be described in two classes:

- (a) Indicating gages, or those gages which require eye readings at certain regular intervals;
- (b) Automatic recording gages.

(a) *Indicating Gages.*

The hook gage.—This well-known device has long been in use and scarcely needs description. A common form is shown in fig. 5. The point of the hook is raised from below the water surface upward by the aid of the screw until the point just punctures the water surface. This setting can be made with great exactness on a stationary water surface if a certain favorable kind of illumination is provided. Settings are a little tedious and may be very inexact during night observations or if the water surface is slightly disturbed. The scale is read by aid of a vernier.

The cup-and-pin method.—This method is also extensively employed. A slender pin is fixed permanently in the evaporation pan and rises to a sharpened point which marks the desired level of the water surface. The pin is best fixed in the

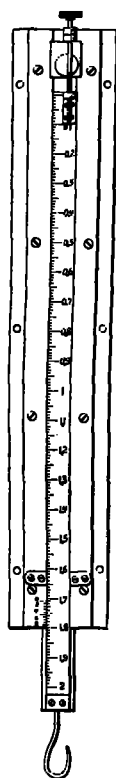


FIG. 5.—Boyd hook gage.

center of the pan and is often surrounded by a tube 2 or 3 inches in diameter so arranged as to realize the still-well conditions. A cup is likewise provided, the contents of which, when filled to the brim and emptied into the evaporation pan, raise the level a predetermined amount, say 0.01 inch. The number of cupsfull that must be added to or removed from the pan to restore the water surface to the level of the pin point represent the evaporation, rainfall, etc., in units of 0.01 inch. This method is also tedious if many cupsfull are required, also errors in the count of cups may easily be made, and the measurement made inexact by splashing and imperfectly filled cups. Obviously a large cup holding say 10 small cupsfull, and itself equipped with a pin point for filling to a definite volume constitutes a possible convenient accessory.

The Lehman pin-and-tank method.—The Weather Bureau official in charge at Birmingham, Ala., has employed a still more useful modification of the pin-and-cup method. His modification adapted to a floating pan is shown in fig. 6. A flower pot *F*, painted above the water line, fixed upon the upper end of the pin *P*, serves as a still-well, and is provided with a mirror *M* to render the point more easily visible. Water to supply that lost by evaporation is drawn from a small cylindrical vessel *A*, provided with a float actuating an index *I*, suspended from a silk thread. The motion of *I* over an appropriate scale shows evaporation in millimeters and tenths.

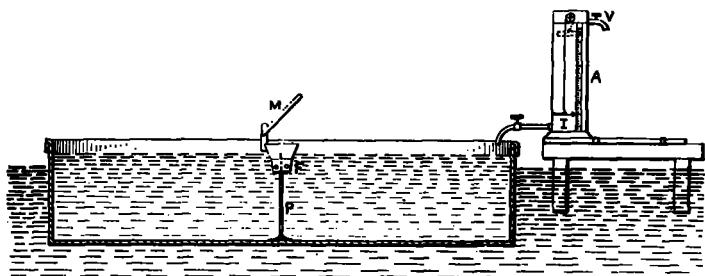


FIG. 6.—Lehman pin-and-tank gage.

The Marvin micrometer gage.—The micrometer gage is a modification of the hook-gage, and in one form or another has also been extensively employed.

Fig. 7 shows a form of the micrometer gage improvised by the writer from easily available material to supply Professor Bigelow's emergency needs at the time the Reno observations were undertaken. A still-well with transparent walls is formed by mounting an argand lamp chimney on the tripod supports shown. Three bits of blotting paper or cardboard¹¹ between the tube and plate suffice to provide any desired still-well relations of water flow. The millimeter micrometer screw and scale [see fig. 8] are carried on a metal spider, *S*, that rests on the top of the glass tube. Settings and readings to the hundredth of a millimeter can easily be made under favorable conditions. The feet of the tripod must be firmly soldered to the bottom of the evaporation pan for continuous service, but it seems the instructions to this effect were not carried out in the Reno and other observations made under Professor Bigelow's directions, and these excellent little instruments were practically discarded by him for general work.

¹¹ Abbe, who has been the only one to use this gage, substituted small slips of oilboard such as is used in letter-copying presses. This has the advantage of retaining its firmness after long submersion and thus not easily affecting the zero-point as used by him.—C. A., jr.

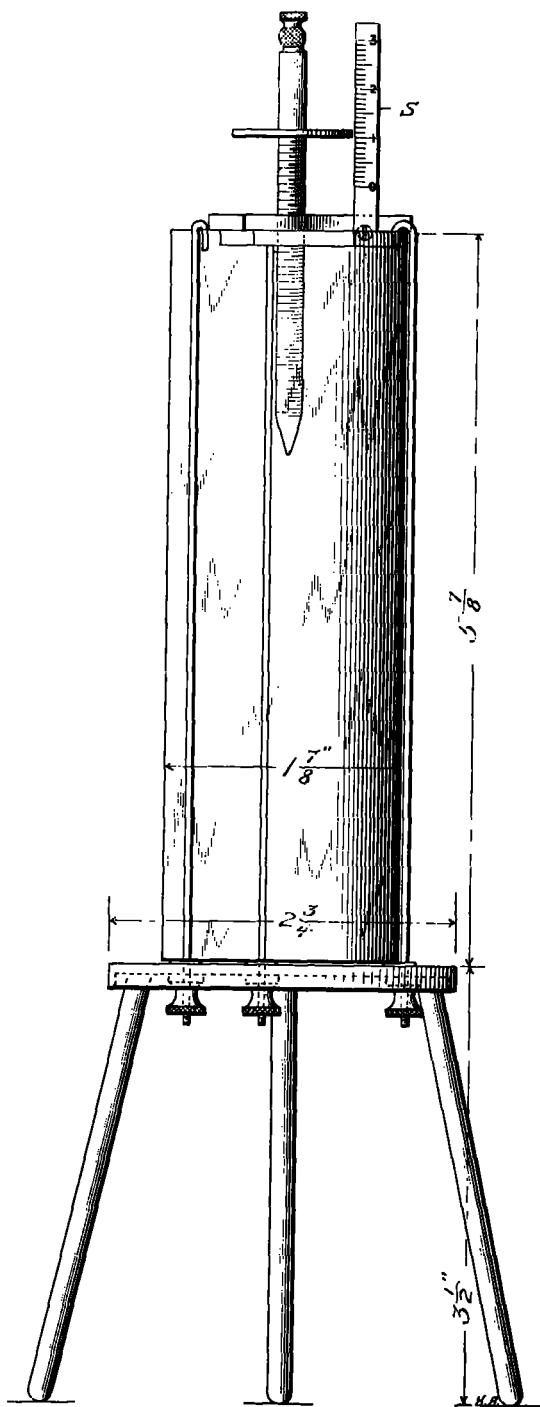


FIG. 7.—Micrometer gage and still-well (Marvin).

All the foregoing methods, if carefully employed, give accurate results under the aid of certain magnifying effects. The pin-and-cup method and its modifications are subject to rather serious constant errors if certain precautions are not observed in evaluating the scales. An error of 1 per cent in a linear measurement becomes an error of 2 per cent on a surface and of 3 per cent in a volumetric result. Many otherwise careful workers will quite disregard this well-known mathematical law. Volumetric apparatus ought to be checked carefully by some sort of actual calibration.

The Bigelow burette gage.—This exceedingly simple device for measuring directly the depth of water in an evaporation pan was introduced by Prof. F. H. Bigelow when making his observations at Reno. It has since been extensively supplied

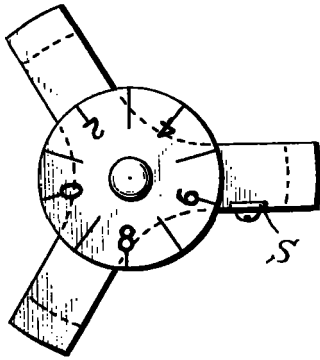


FIG. 8.—Micrometer head for the Marvin micrometer gage.

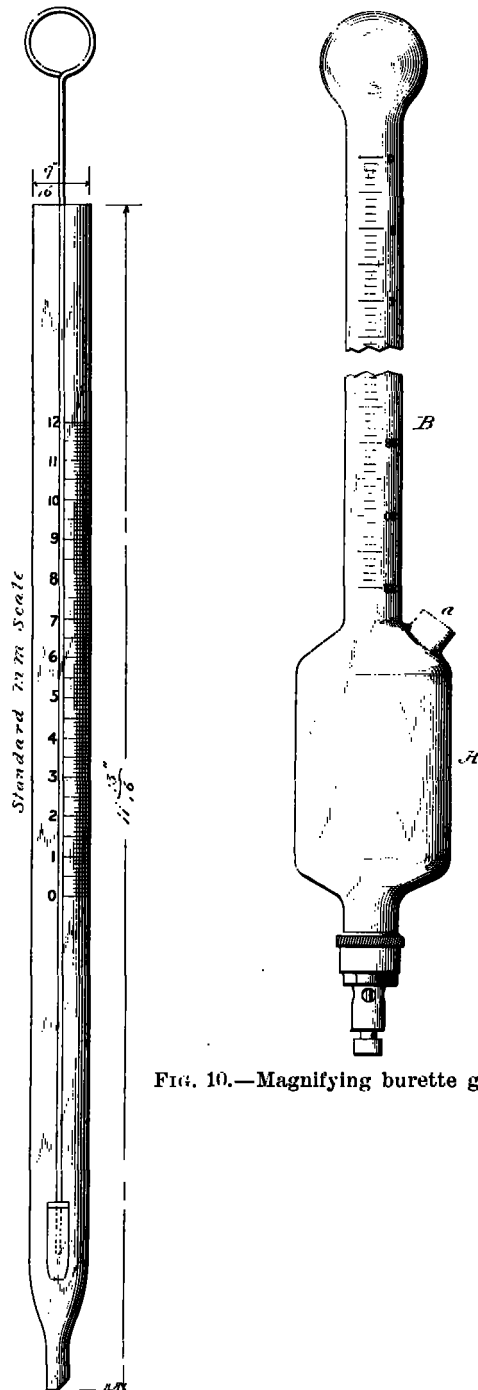


FIG. 9.—Simple burette gage (Bigelow).

in the improved form, shown in fig. 9, to a number of observers at U. S. Irrigation Projects. Professor Bigelow preferred this apparatus to the more exact micrometers because of its simplicity.

A reading is made by placing the point of the tube upon some predetermined spot in the evaporation pan and necessarily this same spot must be used at each observation. The end of the tube is bevelled slightly to admit the water when the stopper is lifted. The graduated tube itself acts as a still-well and when filled the plunger is pushed into the end of the tube. A scale of millimeters engraved on the tube enables one to read off the approximate level of the water. Magnification is impossible with this arrangement and the errors of a reading are probably not less than half a millimeter which of course in many localities will exceed the evaporation for several hours. Such a device will doubtless answer very well where observations are made at wide intervals such as a day or week, but its errors are too large to show up satisfactorily the evaporation during short intervals such as three or four hours.

Marvin magnifying burette.—The Bigelow burette at once suggested to the writer a device by which the measurements could be read on a magnified scale. That is, we can collect the water from the pan in a relatively large tube and pour it into a smaller tube for measurement. The plan was promptly tried by means of an improvised arrangement, and its greater accuracy over the simple burette was shown by a large number of comparative readings made at Washington, D. C., in the summer of 1908. This burette is shown in fig. 10 and its adjustable pedestal in fig. 11.

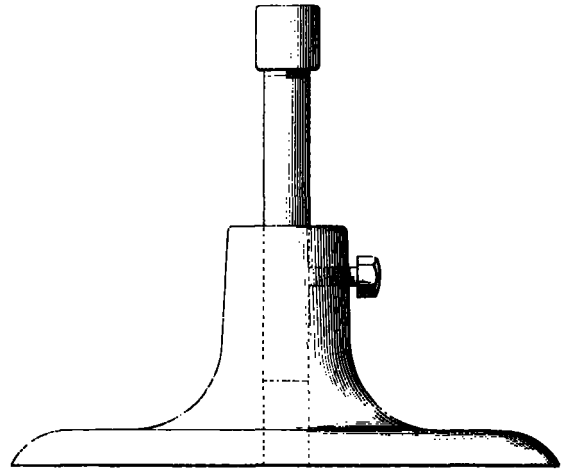


FIG. 11.—Adjustable pedestal, Marvin magnifying burette.

The latter is relatively massive and generally should be placed in the center of the pan which must be solidly supported underneath. The adjustable stem is fixed at such a height that readings are obtained according to the average level desired for the water surface.

The lower end of the burette is fitted with a brass spring valve of simple but reliable construction. To make an observation the burette is held vertically upon the cap of the pedestal with the valve firmly depressed until the water is at a level within and without. The burette itself constitutes its own still-well. The tube being quickly lifted the valve closes instantly and the water is measured by inverting the tube. The scale graduations are 0.2 millimeter (about 2 millimeters actually) and observers are expected to read to the nearest half of a scale graduation, thus realizing tenths of a millimeter in evaporation. The range of scale on the burette embraces somewhat over 30 millimeters and a standard method of manufacture has been perfected so that all burettes of this construction give exactly the same reading in the same pan at the same time. This, at least, is true within narrow limits.

FIG. 10.—Magnifying burette gage (Marvin).

Variations can be treated, if necessary, as instrumental errors just as we sometimes do in the case of thermometers.

It is well known that the adhesion of water to the walls of vessels and variations in drainage on walls temporarily wetted, always interfere with exact volumetric measurements in cases of this kind. These are best minimized by carefully following certain systematic methods of observation or, of course, by repeating readings several times.

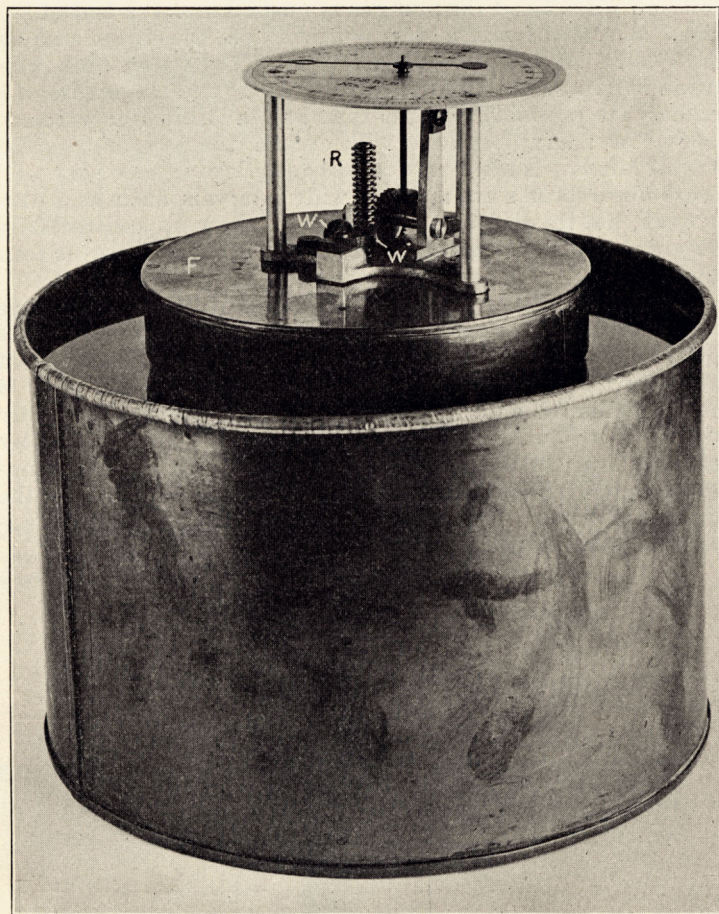


FIG. 12.—Floating micrometer and its still-well (Marvin).

All the devices that have been described thus far have one serious defect. The observer must carefully set and adjust the apparatus according to some fixed and generally more or less tedious method of procedure. This wastes a good deal of time and exacts a good deal of patience. What we really need is a device that will show at a glance and on a magnified scale what the exact level of the water is at any moment. With such an instrument attached to each evaporation pan all an observer is required to do is to read the scale at each observation, and supply water to the pan from time to time. The instrument shown below in fig. 12 meets these requirements in an admirable manner.

Marvin floating micrometer.—The instrument consists essentially of a float *F* that rises and falls with the water surface in the most frictionless manner possible. The float carries a graduated dial and index hand which varies its position with the slightest changes in the level of the water surface supporting the float. In the model of this device at present in operation the dial embraces 30 millimeters change of level and the instrument is operative over a range of about 50 millimeters. The scale of magnification is about 10 to 1; the scale divisions represent 0.2 millimeter, and are over 2 millimeters actual size so that a reading to half a scale division gives

tenths of millimeters on the record.

The mechanical means employed to secure these results are all very simple and of the most reliable character. The still-well in which the micrometer is mounted is provided with a central cylindrical brass stem, *R*, which passes up loosely in a hole through the center of the float. A cylindrical rack, *R*, is cut on a portion of the upper end of this stem, *R*, and a spur gear mounted on the float engages the teeth of the rack in a proper mechanical fashion. The float and gear are always retained in the proper relation by the aid of two little guide wheels, *W*, *W*, arranged for that purpose. Experience shows that a properly constructed gearwheel and rack can be made to engage in this manner and operate with scarcely any serious friction, and at the same time be free from objectionable shake or "lost motion" as the mechanic calls it. By making the rack cylindrical and placing it in the central axis of the float the latter is left perfectly free to rotate about the rack as well as to rise and fall with any variations of water level. This construction, in fact, realizes nearly perfect freedom from friction and the slightest changes of level are at once communicated directly and positively to the gearwheel engaging the rack. It remains only to further multiply this motion and render it measurable. For this purpose a crown wheel formed upon the side of the spur gear drives a small pinion and axle which carries the index hand at the top.

Other devices in which an index actuated by a float is caused to move over a graduated arc have been employed by others engaged in evaporation studies; but these are all subject to narrow and serious limitations and lack many of the distinct mechanical advantages realized in the floating micrometer here described. The float and its multiplying gears, index, and scale are all a self-contained mechanical unit easily manufactured to definite specifications. The dialing and gear-train have no stop points, but admit of indefinite and continuous motion in either direction. The cylindrical rack with its tripod foot also constitutes a separate and definite mechanical entity. To put these in working relation the float is simply lowered around the rack with only sufficient attention to let the teeth of the spur gear enter easily into engagement with the rack. No delicate adjustments or settings of any kind are necessary either when the micrometer is set in action or at times of observation.

The still-well must completely inclose the micrometer to prevent the action of the wind and to protect the mechanisms from dust, insects, etc. Readings can be made through a glass set in the top of the cover of the still-well, but dew is likely to form on the inside under certain temperature conditions. This can be prevented and the metal work protected at the same time against corrosion and the action of the water by adding a thin layer of some light, permanent oil, like kerosene. The form of still-well and siphon shown in fig. 2 prevents any oil getting over into the evaporation pan.

Automatic correction for still-well error.—In discussing the still-well [p. 183] we pointed out the error incident to its use and gave the mathematical expression for finding the true evaporation. The floating micrometer requires a still-well about 6 inches or more in diameter, that is, the still-well area may be about $2\frac{1}{2}$ per cent of the evaporating surface of a 4-foot pan. If, now, the dial indications show the changes of level of the float in *true millimeters* then the scale readings will not give the true evaporation but the quantities will all be $2\frac{1}{2}$ per cent too small. It is possible to arrange the train of multiplying gears so that this $2\frac{1}{2}$ per cent correction is automatically taken up in the motion of the hand. For example, when the float rises say 10 millimeters let the index move over exactly $102\frac{1}{2}$ scale units and we may thus obtain a correct indication of the evaporation.

The advantages offered by the floating micrometer, which

requires only to be read at each observation, seem to render it distinctly superior to any other device that has been thus far offered. It seems to the writer to be almost the only instrument that can be used successfully in the case of floating pans. For this purpose the pan itself must be made perfectly rigid and stiff by appropriate webs and bracing and the still-well must be an integral part of the pan, preferably occupying the center. This whole apparatus will ride on the water with only a relatively small vibration of the index over the scale. In general readings can be made at the limiting positions of the index hand so that a fair estimate may be made of the position of rest under rough weather conditions when scarcely any other method can be employed.

(b) *Automatic Recording Gages.*

In recording evaporation a serious difficulty is encountered in tracing the record of evaporation upon a sufficiently magnified scale and in recording with the same mechanism rainfall that occurs from time to time. To a certain extent these conditions are incompatible especially in regions of heavy rainfall and the best results are then, doubtless, obtained by the use of rain-sheltered evaporimeters as referred to in a separate paragraph.

The writer, after an extensive study of the mechanical problems involved, has developed a form of recorder that seems to meet most of the requirements in a very satisfactory manner. The conditions which he has sought to satisfy may be stated thus:

- (1) Ample scale of magnification, viz, 8 to 1 or greater.
- (2) Small size of the record sheet without waste surface.
- (3) Ability to record rainfall legibly under ordinary conditions, i. e., at rates as high as 5 or 6 inches per hour in quantities of 1 or 2 inches or more.
- (4) General simplicity of mechanisms of a durable character, small size, portable, easy to install, etc.

Marvin's triple recorder.—These requirements are scarcely satisfied, as a whole, by any of the instruments that have been described heretofore, as far as known to the writer, but their realization must necessarily result in a very satisfactory form of apparatus.

In the instrument we have devised along these lines we have added a very important accessory, namely, a recording pen which traces a record of the wind movement by the aid of the ordinary anemometer installed in any manner desired in close proximity to the evaporation pan. Thus we obtain continuous records side by side on the same sheet of *rain, wind, and evaporation*. The original model of this instrument is shown in fig. 13, on a special base plate arranged to exhibit the mechanisms. In actual practice the whole instrument is inclosed in a compact metal case comprising the still-well. The distinctive feature of the instrument is found in the devices employed to magnify and inscribe the movements of the customary float resting on the water surface in a suitable still-well. For this purpose we use a small, fine, smooth gilded chain such as goldsmiths employ to string jewel necklaces. These chains are very strong and inextensible yet almost perfectly flexible. A piece of such a chain passes over a drum, *D*, causing it to revolve as the float, attached to one end of the chain, rises or falls with the water surface. A small counterweight, *W*, produces a sufficient tension on the chain. Increased driving effect can be gained by wrapping the chain one or more times about the drum, which is made of ample width of face for this purpose, or it may be screw-threaded if desired.

The axle of the drum is provided with a crown wheel and pinion combination, *C*, which greatly magnifies the effect of the slight motions of the float. The vertical axis of the pinion carries a crank disk at the top, which by the aid of a light pitman rod communicates a reciprocating movement to the pen carrier pivoted at *A*. The pen arm proper is pivoted

in a fork *F* of the carrier. This construction serves the double purpose of permitting the pen arm to be lifted entirely back, clear of the record drum, and at the same time by the aid of a suitable weight at *a* the pressure of the pen point on the record sheet can be reduced to the minimum compatible with a perfect record. All these arrangements will be readily understood, it is believed, from an inspection of the illustration.

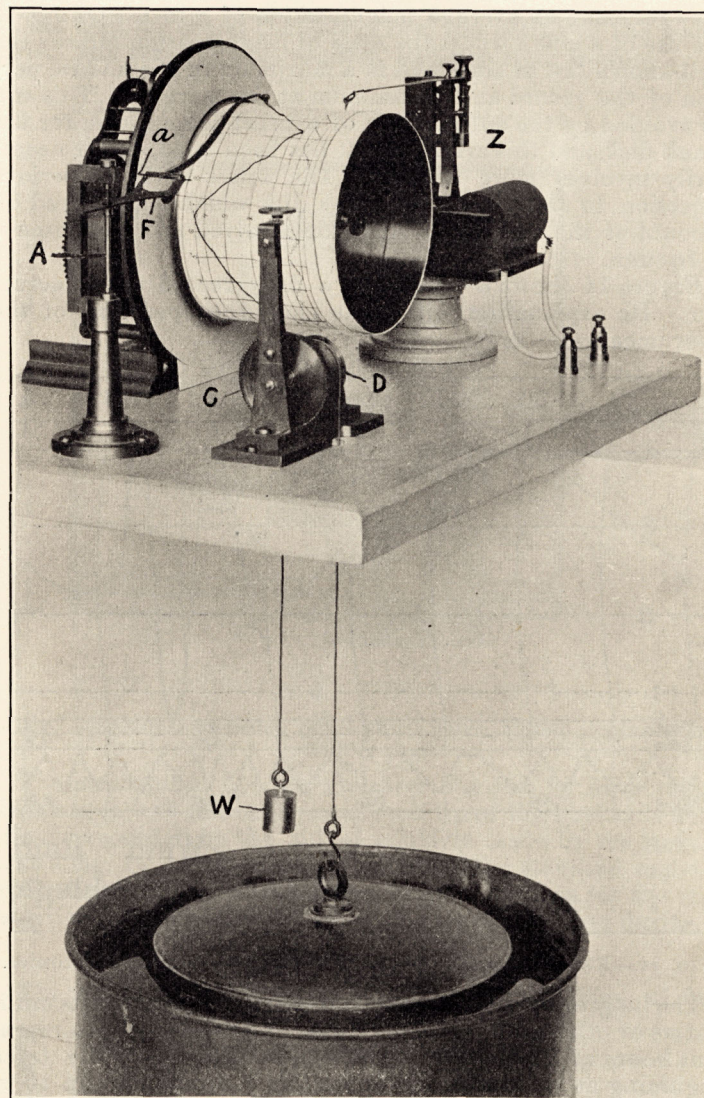


FIG. 13.—Rain, wind, and evaporation recorder (Marvin).

The mechanisms we have described involve the minimum amount of friction consistent with the work that is to be done, and to render the action as perfect as possible we employ small ball-bearing pivots of neat and simple design on the axle of the crown wheel and drum, which give the maximum strength with the minimum friction. The float required in recording evaporimeters is often of seeming grossly disproportionate size. This is because excessive friction exists in the magnifying and inscribing mechanisms. For example, we must be able easily to read to tenths of a millimeter of evaporation and the recording pen must respond continuously to much smaller movements of the float than this. If the mechanisms stick slightly as the evaporation goes on steadily then the movements of the pen will take place by starts and jerks and this will give the record a steppy discontinuous appearance. A change of water level of one-tenth millimeter on a float 20 centimeters in diameter introduces a moving force of 3.1 grams. This is quite adequate to move the multiplying and

recording devices we have employed and experience shows that a float of this size gives a smooth and continuous record.

Form of record.—When the float moves continuously downward, for example, the pen reciprocates back and forth across a prescribed space upon the record sheet. The dimensions of the drum and the ratios of crown wheel, pinion, crank arm, and pen levers are such that the pen makes one transit across the sheet, 40 millimeters, when the float moves 5 millimeters, thus realizing an average magnification of 8 to 1. Owing to the use of a crank wheel the scale of magnification follows the well-known law of sines and is a maximum in the middle portion of the record and a minimum at the margins. This can be avoided by the substitution of a heart-shaped cam for the crank disk, and this arrangement has been tried, but it necessarily involves more friction. The writer finds no serious objection to the use of the crank disk which is preferred on account of the simpler construction involved and the absence of friction.

Figure 14 shows a portion of a daily record sheet, actual size. Its explanation will make clear the operation of the instrument.

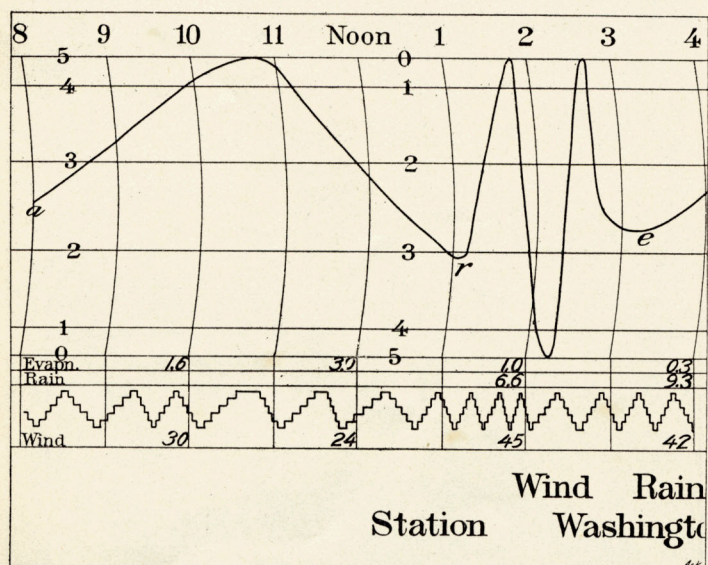


FIG. 14.—Record of the Marvin rain, wind, and evaporation recorder.

The longitudinal lines numbered 1, 2, 3, etc., represents millimeters or other units of evaporation. The vertical lines represent hours of time. The record starts at the left, the trace beginning at *a* indicates evaporation continuously up to *r*, when about 5.6 millimeters of evaporation had been recorded. At this point the pen stopped and began to move backward without having reached the limit of its reciprocation; this means that rain caused the float to rise, i. e., from the point *r* to the next reversal of the motion between the margins of the sheet, for example at *e*, the record represents rain. The record beyond *e* must be read as evaporation. It may seem at first thought that the rain and evaporation can not often be separated. This, however, is hardly the case. There are two reasons why it will generally be easy to disentangle such composit records. *First.* The change from evaporation to rain and vice versa, will almost always fall between the margins of the record and any reversal of the motion of the pen, *between the margins of the record* always means a change from evaporation to rain, or from rain to evaporation. *Second.* The rate of evaporation is always very slow and mostly regular, whereas rain falls at very irregular and often at very rapid rates. It is, of course, possible that rain may, for example, begin to be recorded just as the pen reaches the margin of the sheet so that the actual reversal of the motion of the float is not dis-

coverable on the face of the record. In such cases we must rely on the other characteristics to differentiate the records, and it is believed that difficulties and confusion of records on this account will be inconsequential.

Wind record.—The device *Z* employed to record the movement of the wind is the zig-zag apparatus used at U. S. Weather Bureau stations in the registration of rain and sunshine.¹² Its reliability has been abundantly demonstrated by years of satisfactory service. The record needs but little explanation. Each step in the zig-zag trace represents a mile or a kilometer of wind movement. These fall in groups of five up and five down or vice versa, that is, each complete apex, \wedge , represents ten miles or kilometers, etc. Notwithstanding that the record sheet moves at the slow rate of less than half an inch per hour yet this device enables us to inscribe a perfectly legible record of winds of such extreme velocities as 90 to 100 miles or kilometers per hour.

The record sheets must be changed each day, but records can easily be provided for upon a continuous ribbon of paper, if required. Good results in evaporation, however, require frequent attention to the water in the evaporation pans, which often becomes quickly fouled and must be refreshed and the level of the surface maintained at a proper point below the rim of the pan. On these accounts the writer is strongly in favor of daily records, and the slight attention to the apparatus thus entailed greatly enhances the value of the record.

Evaluation of record sheet.—The scheme proposed for evaluating and tabulating the recorded data is indicated in fig. 14. The data is read from the record for intervals of two hours each. Thus, in fig. 14 the evaporation during the first two hours of the record was 1.6 millimeters; from 10 hours to 12 hours the amount shown is 3.0 millimeters, etc. These amounts are set down on the record sheet in the spaces provided; the rain

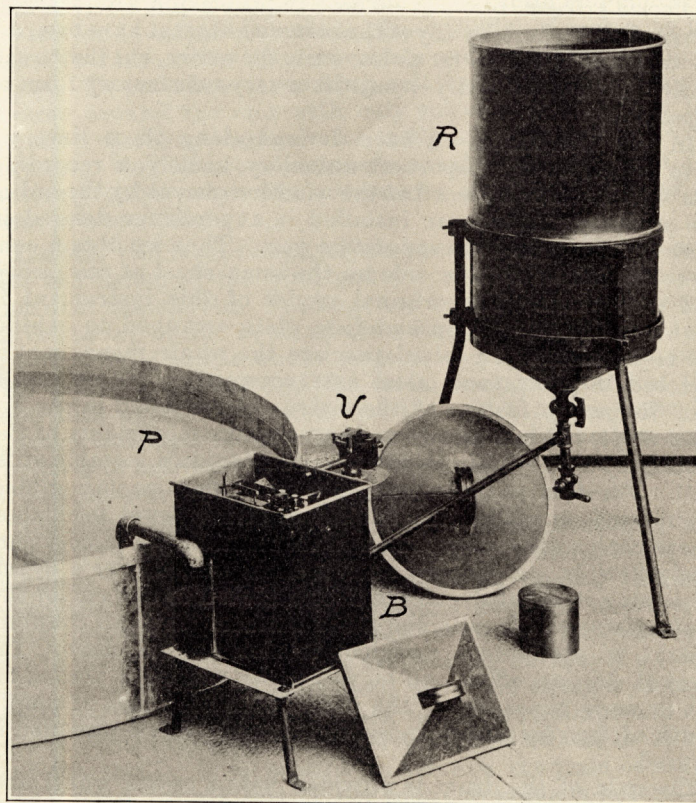


FIG. 15.—General view of the recording evaporation gage, tipping-bucket system (Marvin).

¹² A detailed description of this attachment is given in W. B. Publ. No. 364, Anemometry, Circular D, Instrument Division. 1907.

and the wind being treated in the manner just explained for evaporation.

Tipping-bucket electrical recorder.—The measuring mechanisms of this apparatus are shown assembled in working arrangement in fig. 15. The rectangular box and cover shown at *B* serves as a still-well in connection with the evaporation pan, and contains a tipping-bucket device operating in conjunction with a float so as to replace the water lost by evaporation and record the amounts thus supplied. The water required for this purpose is drawn from the reservoir, *R*, through an electrically-operated valve imperfectly seen at *V*. (See also fig. 17.)

The float and tipping-bucket mechanisms are shown diagrammatically in fig. 16, at *F* and *B*, respectively. The float is poised on a delicately supported multiplying lever *L*. As the level of the water slowly falls from loss by evaporation, the free end of the lever, *L*, rises in a magnified proportion. A small electromagnet located near the end of the lever is actuated momentarily once each minute by a contact in the clock of the register. Ordinarily nothing results from this action, but sooner or later the free end of the lever rises to such a point that it is caught and pinched by the closure of the electromagnet. The pinching of the end of the lever when

the tipping-bucket alternately rests. Consequently, the instant the bucket starts to tip the electric circuit is opened, the flow of water cut off, the free end of the lever released and the float elevated by the water emptied from the tipped bucket. The flow of the water from the still-well to the evaporation pan is slow and deliberate, and since the float, *F*, is itself inclosed within a small compartment, oscillations are most effectually suppressed. In the tests of this apparatus at Washington before it was sent for use at the Salton Sea, the action of the mechanism was very regular, positive, and free from trouble.

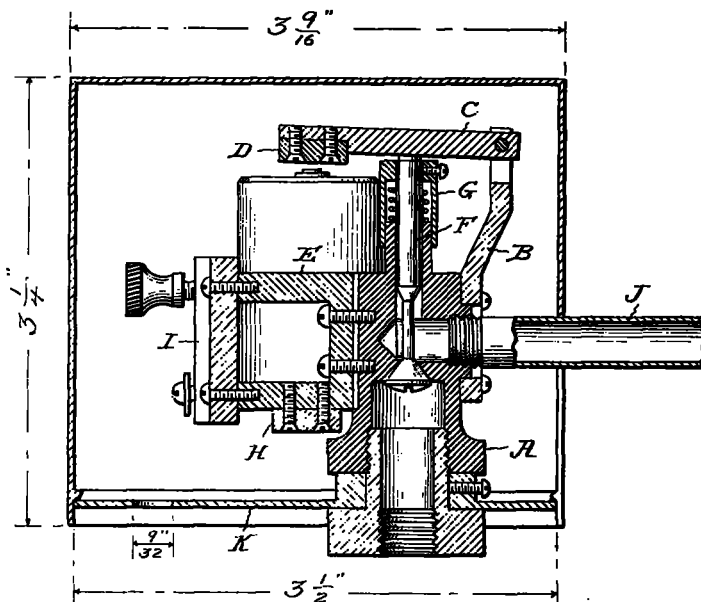


FIG. 17.—Sectional elevation of electrical valve, Marvin tipping-bucket recording gage.

The mechanisms operate whenever the loss by evaporation amounts to 0.05 millimeter, and each tip of the bucket is electrically recorded by the aid of contacts made by the spring, *c*, at *a*, fig. 16. This record is made on the standard register extensively employed at Weather Bureau stations for the registration of rainfall by the aid of the tipping-bucket device.

Auxiliary Apparatus.

The study of evaporation requires a knowledge of the

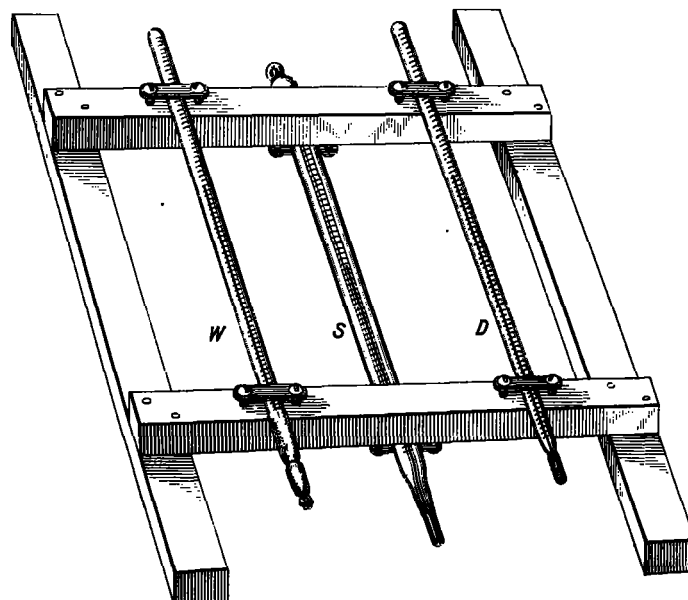


FIG. 18.—Thermometer raft.

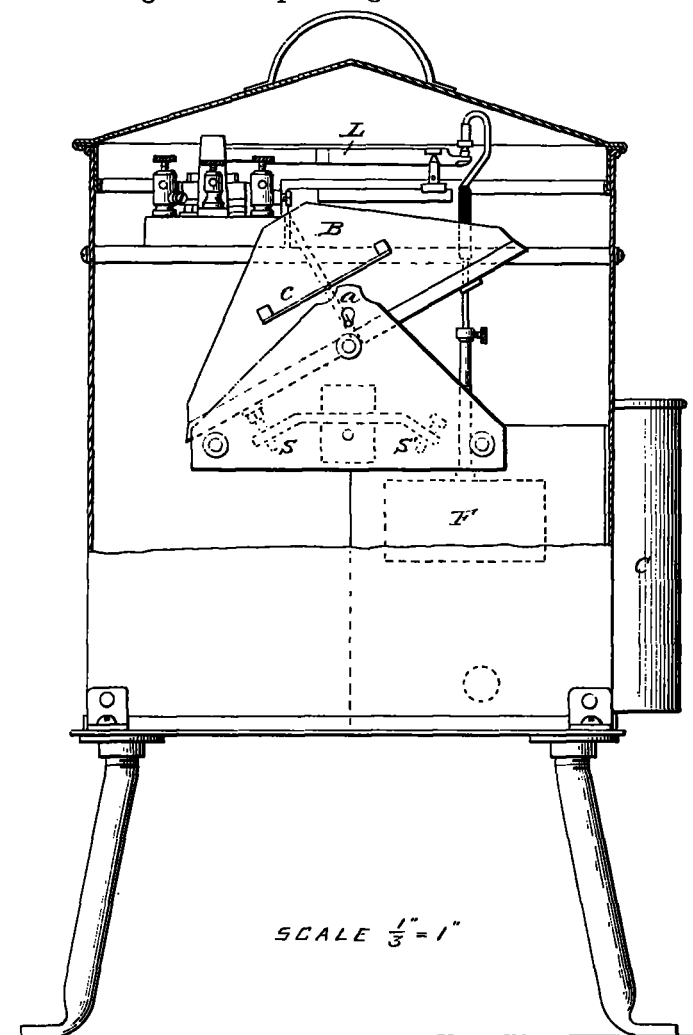


FIG. 16.—Sectional elevation of still-well, float, and tipping-bucket (Marvin).

it has risen to the critical height effectively closes the electric circuit through the valve *V* shown in cross-section in fig. 17. This starts the flow of water from the supply tank, *R*, and the tipping-bucket is quickly filled. The electric currents for all these operations pass through the stop pins, *S*, *S'*, upon which

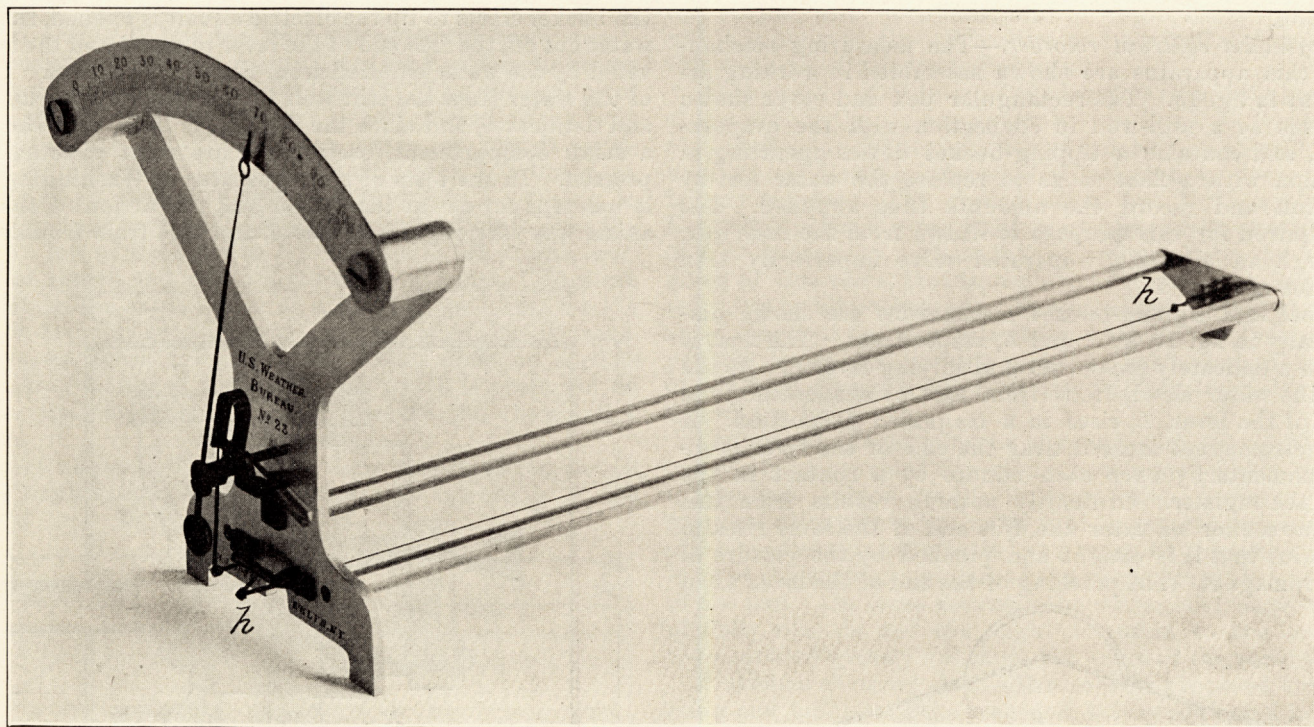


FIG. 19.—Hair hygrometer (Marvin).

velocity of the wind, the temperature of the water surface and the temperature and moisture content of the air at one or more points in the near vicinity of the evaporating surface. Some instruments and devices suitable for these purposes are shown in figs. 18 to 20.

Anemometer.—This well-known instrument requires no special description. The chief complication in its use arises from the difficulty in placing it in a position such that its record gives a true measure of the wind movement over the surface of the water whose evaporation is being studied. A number of observers when discussing evaporation data have used wind observations from anemometers many feet above and often at considerable distances from the evaporation pans. Accurate conclusions are quite improbable under such conditions.

The thermometer raft.—This arrangement was devised for Professor Bigelow's Reno observations and is shown in fig. 18, with the proportions and spacings finally adopted. When floating on a water surface the bulb of the thermometer, *S*, is just submerged and gives the temperature of the water surface. This thermometer is of the well-known glass-jacket construction with the scale of graduations inside the jacket tube. The two remaining thermometers are carried about one centimeter above the water surface, the bulb of *W* being properly covered with muslin, a loose end of which dips into the water, so that the combination, *W*, *D*, serves as a psychrometer for the purpose of giving a measure of the temperature and vapor pressure near the surface of the water.

The results obtained by this arrangement can not be regarded as highly accurate. In the first place, no attempt is made to cut off radiation and insolation; secondly, the ventilation of the psychrometer is quite inadequate, except when there is a good wind blowing. At such a time the readings of the instruments no doubt give very nearly exact values.

There is, however, another cause of error that is mostly overlooked. In the use of these rafts up to the present time, the practice has been to place the raft in the water of the pan

a few minutes before each observation. Now, during periods of comparative calm the blanket of vapor near the water surface becomes nearly saturated for a considerable thickness. Careful observations made by the writer show that it is impossible to place the thermometer raft in the water without completely breaking up the vapor blanket. Consequently, observations made in this manner when the air over the evaporation pan has been relatively quiescent for some time are likely to show a much smaller vapor pressure than existed before the vapor blanket was disturbed by the operations incident to placing the raft and making the observations.¹³

Hair hygrometer.—The writer has used the form of hair hygrometer shown in fig. 19 for making studies of the vapor blanket very near the water surface. The slender strand, *h*, *h*, of a few hairs can be placed parallel to and, if desired, very near the water surface.

The hair hygrometer can hardly be regarded as a reliable primary instrument, but by frequently checking its readings with the sling psychrometer entirely reliable results are possible while its great sensitiveness and other qualities enable one to get data which can hardly be obtained otherwise.

Sling psychrometer.—This well-known instrument is shown in a convenient form in fig. 20 and scarcely requires further description. Faulty results have attended the use of the sling psychrometer at some of the evaporation stations from a disregard of the long-standing instructions respecting the wet-bulb covering. Only thin, finely woven, linen or muslin should be used and, if new, this must be thoroughly washed in clean water before applying to the bulb, so as to completely remove sizing, etc. The covering must be first wetted to apply to the bulb, and be carried up around the stem above the

¹³ In Abbe's observations at Indio, Cal., in November, 1907, the psychrometer was uniformly whirled in the air over the center of the pan and as close as feasible to the water surface. This procedure churns the air and disturbs the vapor blanket in a much more serious manner than the mere placing of the raft in position, so that observations thus obtained in still air must be erroneous.—C. A., jr.

bulb for a distance of half an inch or more, so as to cool this part of the thermometer as well as the bulb. It must be wrapped close and tight for not more than one and a half turns around the bulb. The free end below the bulb must be tied in closely and left projecting for an eighth of an inch or more. The psychrometric formula and tables are computed for this sort of covering. Failure to wash out the sizing in new muslin or a wrinkling of the covering so that it fails to fit the bulb closely, is likely to give erroneous readings.

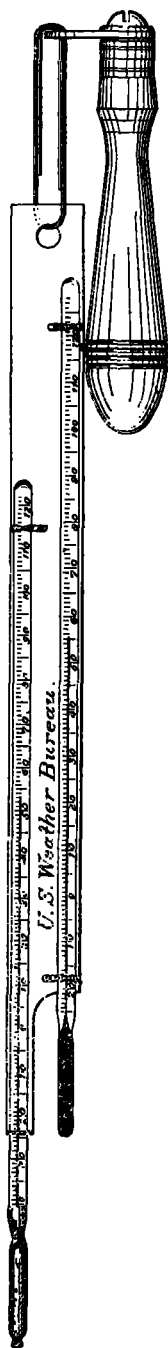


FIG. 20.—Sling psychrometer (Marvin).

METEOROLOGICAL OBSERVATORY AT TENERIFFE.

We are pleased to announce that the Spanish authorities are cordially cooperating with the International Aeronautical Commission and the German Government in supporting the high-level meteorological observatory on Teneriffe. It has been decided to open the doors of the observatory to qualified investigators of all nationalities.—C. A., jr.

THE RELATIONS OF THE INVERSIONS IN THE VERTICAL GRADIENT OF TEMPERATURE IN THE ATMOSPHERE TO AREAS OF HEAT AND COLD.

By HENRY HELM CLAYTON. Dated Readville, Mass., March 2, 1909.

When recording instruments are sent aloft on kites or balloons they show that, at least in the lower air, the temperature usually falls with increasing height above the ground; but there are belts or regions where the temperature rises with increasing height above the ground. These regions of rising temperature have received the name of inverted gradients. The belts of inverted gradient play an important part in atmospheric phenomena. They separate the air into strata with marked contrasts in humidity, wind velocity, and cloud formation. Usually the maximum of humidity and the clouds are immediately below the inverted gradient, but sometimes this condition is reversed. Usually there is a maximum of wind velocity within or very near each inverted gradient which occurs within 4,000 meters of the earth's surface. There are undoubtedly many other important relations to meteorological phenomena which remain to be disclosed.

Studies of these inversions have been made by Rykachev,¹ Assmann,² A. J. Henry,³ and myself.⁴ The conclusion which I reached⁴ from a study of the data at Blue Hill was that "the belts of inverted gradient reached their greatest distance from the ground about the time of minimum temperature, and were nearest the ground about the time of maximum temperature."

In a recent study of the records obtained with kites and sounding balloons on the expedition of M. Teisserenc de Bort and Professor Rotch in the trade wind region, I found that the inverted strata dipped from about 40° north to the heat equator and then rose again in southern latitudes. Hence, I am led to conclude that it is a general law for the inverted gradients of temperature to incline upward from regions of warmth toward regions of cold, and vice versa.

The reason of this rule is probably because air flowing from regions of cold towards regions of warmth has a descending component of motion and the inclination of the inverted gradient indicates the angle of descent. On the other hand air moving from regions of warmth toward regions of cold is ascending and the inclination of the inverted gradient indicates the rate of ascent. But ascending air is expanding and cooling so that in time the moisture in such inclined ascending currents becomes condensed into cloud and in this way is undoubtedly to be explained the presence of stratiform clouds such as nimbus, alto-stratus, cirro-stratus, which are found immediately beneath these inverted gradients.

How the inverted gradients dip downward as the temperature of the air in which they occur rises and how they ascend as the temperature falls is here illustrated by some examples taken from my discussion of the observations at Blue Hill in Bulletins No. 1, 1899, and No. 1, 1900, of the Blue Hill Meteorological Observatory. Figs. 1 and 2, in the accompanying diagrams, show plots of the temperatures recorded at different heights on September 21 and 22, 1898, when the temperature was rising. Dots connected by a continuous line show the points where the temperature was read from the records made during the ascent of the kite and crosses connected by a broken line show the temperatures during the descent of the kite. It is seen from fig. 1 that the inverted gradient was between 1,200 and 1,700 meters during the ascent on September 21. By the morning of September 22, see fig. 2, the temperature had risen some 10° to 15° F., and the inverted gradient had descended several hundred meters. During the descent of the kites on the afternoon of the same day the inverted gradient had descended to within 650 meters of sea-level.

¹ Meteorol. Zeitschr., Hann-Band., p. 174.

² R. Assmann, Beiträge z. Physik d. f. Atmosph., 1:39.

³ Bul. Mount Weather Observ., 1908, 1, pt. 3:143.

⁴ Bul. Blue Hill Meteor. Obs., 1900, No. 1:7, 11.